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Abstract

The mobile and increasingly ubiquitous use of information technology leads to more dynamic, constantly self-reconfiguring networks. Their services are available anytime and anywhere; as software agents, they can make local, context-aware decisions. F. A. von Hayek developed a theory for economic coordination based on individual decision making. This paper presents the explanation concepts of economic self-organization as at least one option for the design of decentralized coordination of information systems consisting of autonomous software agents with limited information processing capacity and incomplete information. Experiments using a multi-agent system show that a targeted change of this basic rule set directly influences the behavior of the individual elements and indirectly the behavior of the overall system.

Keywords: Self-organization, Catallaxy, software agents, ubiquitous computing, decentralized coordination, distributed systems, Hayek.

Self-Organization in Hayek's Catallaxy

> "Realistically, an organization of the unknown is only achievable by inducing its self-organization.
> (Hayek 1988)

The lifework of Friedrich August von Hayek (Hayek et al. 1989) lays the foundation of this article. His understanding of the market as a coordination mechanism and the combined concept of the Catallaxy is mainly reduced to being the subject of ideological discussions about the advantages of markets in relation to a command economy. However, his work provides also concrete insight on the working mechanisms of economic coordination, which might now be applicable to upcoming types of information technology. The emergence of software agent technology and increasing mobility and miniaturization of digital end user devices leads to the possibility of constructing information systems with no central command point. This gives rise to the idea of using Hayek's Catallaxy concept and the ensuing "spontaneous order" as a concrete proposal for both the design and coordination of information systems.

However, a formal description of this self-organizing market mechanism does not so far exist. In the research field of agent-based computational economics (Tesfatsion 1997), economists and computer science try to provide formal descriptions and to build computer simulations. If the mechanisms can be properly understood, it might be able to build large multiagent information systems using the Catallaxy approach, where artificial entities coordinate themselves just as human economy participants do in the real world.

This article does not discuss the advantages of self-organization for the design of information systems in an abstract form, but essentially presents the findings of experiments with multi-agent systems conducted in Freiburg for some years (Eymann 2000;

Padovan 2001; Sackmann 2003). After this brief introduction of the Catallaxy concept and the technical trends of information technology, the article demonstrates using the application example of agent-based supply chain management that coordination can be achieved in a emergent, self-organizing way. This "spontaneous order" can be improved on the level of the entire system by modifications of the regulatory framework, and by adaptation of the individual behavior of the actors.

Self-Organization in and Through Information Systems

If new decentral technologies like *ubiquitous computing* (Weiser 1991), grid *computing* (Anderson und Kubiatowicz 2002)or peer-to-peer *computing* (Schoder, Fischbach und Teichmann 2002) are to be simple updates of existing technologies, nothing would have to change in the system design. The productivity gains provided by information systems would be given through technological progress alone. Decentralized interaction and spontaneous networking, however, also allow organizational in addition to technical progress, which – as a hypothesis – could include self-organizational control possibilities and makes rationalization gains attainable far beyond technology.

In order to search for existing and proven examples and artifacts of self-organization, one finds the biological evolution, the human autonomic nervous system, economic markets and, more general, complex adaptive systems (Kauffman 1995). The biological metaphor for example serves as the foundation for IBM's approach on Autonomic Computing (IBM Corp. 2001). The focus of this article, however, lies in economic approaches to self-organization.

Basically, (information) systems can be described as self-organizing when the following properties are present (Müller et al. 2003; Probst 1992):

(1) Complexity: A self-organizing system is a complex network of reciprocally influencing interactions. The relations between the individual components are dynamic; any change can thereby alter an existing order or produce a new one through the local, self-serving optimization of the components.

(2) Autonomy: A self-organizing system controls itself within a given regulation framework, which limits action possibilities of the individual components and is defined in the form of prohibitions. The relations and interactions within the system are endogenously induced and result in system-wide models.

(3) Redundancy: There is no lone "organizer" responsible for the design of the system. Decisions are made decentrally by redundant components which have only incomplete, directly available information and limited processing possibilities at their disposal. A view of the entire system and knowledge of the interdependencies does not exist.

Beginning with Adam Smith's description of the "invisible hand" (Smith 1776), economists describe market participants as competing for limited resources and coordinating themselves through pursuance of their own goals. Hayek's Catallaxy (Hayek et al. 1989) is a later and similarly decentralized concept of the neo-austrian school of Economics, as opposed to the centralized Walrasian auctioneer and Keynesian computable general equilibrium approaches. The term Catallaxy derives from the Greek word *katallatein*, which means "barter" and at the same time "to join a community". The goal of Catallaxy is to arrive at a state of coordinated actions, the "spontaneous order", which comes into existence by the community members communicating (bartering) with each other and thus achieving a community goal that no single user has planned for. If one tries to sum up the elements which constitute Catallaxy, its central characteristics are (Hoppmann 1999; Hayek et al. 1989):

(4) Participants working in their own interest to gain income. Every system element is a utility maximizing entity, which requires the definition of utility itself, of means to measure and compare income and utility, and to express a desire to reach a defined goal. For humans, these definitions have not necessarily to be explicit or thoroughly defined; for information system elements, this explicitness is required.

(5) Participants subjectively weigh and choose preferred alternatives in order to reach an income or utility maximization goal. In economic theory, the "homo oeconomicus" is a completely rational utility maximizer, in that he can choose an alternative action out of total knowledge about the environment, which then maximizes his utility. Hayek's claim was that such an "objective" choice is not possible because of "constitutional ignorance", which takes into account that it is (inevitably) impossible to know each and every environment detail that determines the agent's action. For large and very dynamic information systems, this is inherently true, and overcoming it by central means requires synchronization and restriction of possible actions of the single elements.

(6) Participants communicate using commonly accessible markets, where they barter about access to resources held by other participants. The development of prices for a specific good, whether they are increasing or decreasing, leads buyers to look for alternative sources of procurement and thus enhances the dynamics of the market. Note that a market here is nothing more than a communication bus – it is not a central entity which collects all information and matches market participants using some optimization mechanisms, which would contradict "constitutional ignorance".

Earlier work in the context of computer science has used economic principles for resource allocation in operating systems, packet routing in computer networks, and load balancing in distributed computer systems (Clearwater 1996; Huberman 1988). Most of these approaches rely on using a centralized auctioneer and the explicit calculation of an equilibrium price as a valid implementation of the mechanism (Wellman 1996). A successful implementation of the Catallaxy paradigm for a distributed resource allocation mechanism promises the advantage of a more flexible structure and inherent parallel processing compared to a centralized, auctioneer-based approach. However, we first have to look whether information technology exists which allows to realize systems where this goal is achievable.

Enabling Self-Organization Through Technical Development

Two development trends have the potential to change the utilization and deployment fields of information systems on a broad basis. Firstly, the mobile utilization of information systems provides man with global accessibility, simultaneously retaining the accustomed services. Secondly, the embedding of computers leads to an "omnipresence" of information. This hardware development requires software systems which control and coordinate the interaction between an infrastructure of ubiquitous computers and an application domain (see figure 1).

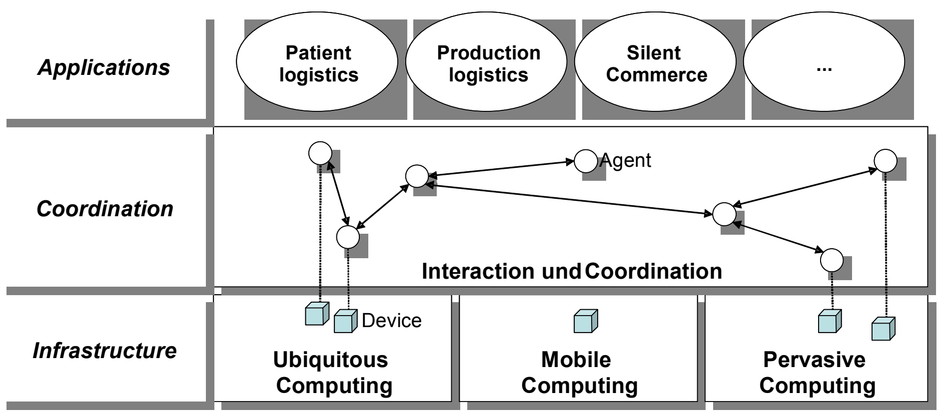

Figure 1. A Layered Model for Decentralized Information Systems

A differentiation is currently being made between three separate development directions on the basis of the properties of "mobile", "context sensitive" and "ubiquitous" (Lyytinen und Yoo 2002; Müller et al. 2003):

In the case of mobile computing, the access devices physically move with their owners and with them the access to IT services. A characterizing feature of *mobile computing's first phase* (Müller, Eymann und Kreutzer 2002) is that the notion or constitution of the service provisioning – apart from mobile access of the clients – does not differ from the stationary case.

In the case of pervasive computing, a device uses environmental information for a permanent and seamless adaptation of its internal reality modeling to a constantly changing reality (Mattern 2001). This requires an intelligent or "smart" environment which discovers an infiltrating device and communicates with it via its sensors or communication interfaces.

Finally, ubiquitous computing (UC) combines the two preceding developments. Every computer continuously interacts with the environment whilst in motion. Services and internal reality modeling constantly and independently adapt to the reality (Banavar und Bernstein 2002), whereby the individual devices greatly differ in their potential and resources. They can form "meta services" to compensate through communication with the environment which are rendered possible through the spontaneous networking of mobile and stationary devices in close proximity and their services. Ubiquitous computing thereby presents a *second mobility phase*, in which devices offer each other services according to their means, i.e. are alternately available as server and client.

For human users, these developments will cause a change in awareness, utilization and dealings with information technology. Some computers will not be able to engage the full attention of the user on every occasion. They will rather have to be "intercepted" through a far-reaching autonomy of software in terms of "calm technology" (Weiser und Brown 1996). Software agents present a promising technology which can act autonomously on behalf of the owner in a predefined way, as for example the purchasing of a ticket when entering a train or paying for shopping when leaving the supermarket (Adams, Ferguson und Tobolski 2003). The interactions of the resultant multi-agent systems (MAS) (Weiss 1999) on the application domain are, however, a necessary subject of current and future research.

Spontaneous Order in Multi-Agent Systems

This section shows the potential of the combination of IT technology and self-organization by presenting experiments done in the multi-agent system AVALANCHE and its successor B2B-OS (Eymann 2003). The application example is a simple model supply chain management problem.

Software agents here represent enterprises of the wood-processing industry at various net product stages (lumberjack, carpenter and cabinetmaker, see figure 2) and independently carry out business activities on behalf of their user. They operate as automated producers (Kephart, Hanson und Greenwald 2000), who purchase the necessary input factors from other agents on the electronic marketplaces, transform them through a (simulated) production process into an intermediate or end product and, in turn, sell the manufactured product to other agents. The agents map and alter the current state of their environment through the direct communication of price information via purchasing and sales offers with other agents or through interfaces to databases, catalogs, auctioneers or other service providers. Their internal model maps the actual state of the market and decides here on the type of action on the basis of a heuristic strategy. This strategy is adapting using machine learning mechanisms (Goldberg 1993), and this constant revision of strategies leads to a co-evolution of software agent strategies, a stabilization of prices throughout the system and self-regulating coordination patterns (Eymann 2001). The resulting patterns are comparable to those observed in human market negotiation experiments (Pruitt 1981).

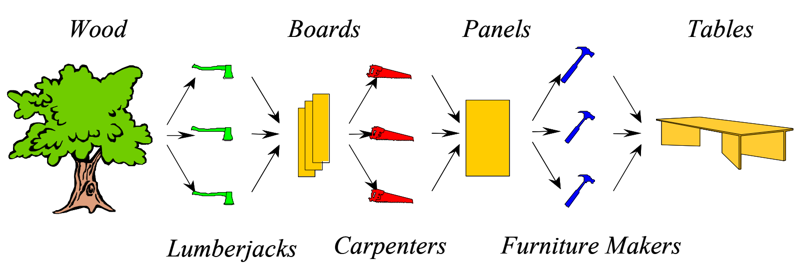

Figure 2. Model Supply Cchain for Experiments

During the information phase (Müller, Eymann und Kreutzer 2002; Lindemann und Schmid 1999), the purchasers and/or sellers choose potential transaction partners through random selection. In the negotiation phase, an agent initiates a bilateral price negotiation and alternating bids are exchanged according to a monotonic concession protocol (Rosenschein und Zlotkin 1994) until an agreement is reached or negotiations are broken off (see figure 3). The buyer agent initiates a negotiation by proposing a seller, whose address was obtained from reading the white board, sending a *propose* message containing the sender *A*'s identity, the receiver *B*'s identity and the particular offer price *x*. The receiver B has now the choice between downright accepting the price, making a counter-offer, or refusing to further negotiate at all. Whether the state transaction from state *a* to either states *b* (propose), *c* (accept), or *i* (refuse) is executed, depends on the action decision made in the agent's internal model. The negotiation continues until either a deal has been landed (state *g*) or one of the agents has unilaterally decided to refuse further negotiation (state *i*).

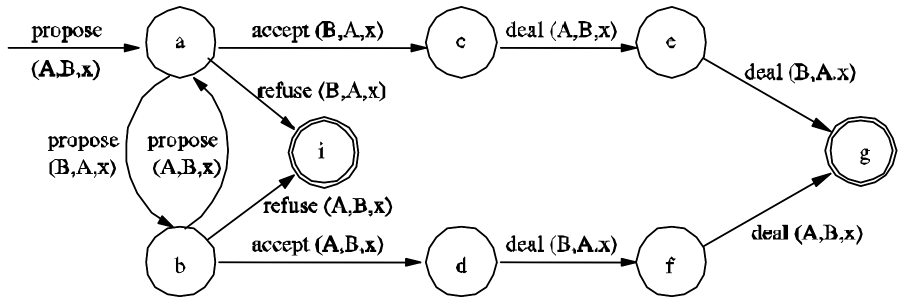

Figure 3. Course of a Negotiation between Two Agents A and B

In the control and adaptation phase, the execution of the transaction is carried out and monitored by the agents. The transaction price realized alters the subjective estimation of the market price for both agents with corresponding feedback on the strategy. The initial price with which an agent enters into the negotiation is increased or decreased for the purpose of utility maximization.

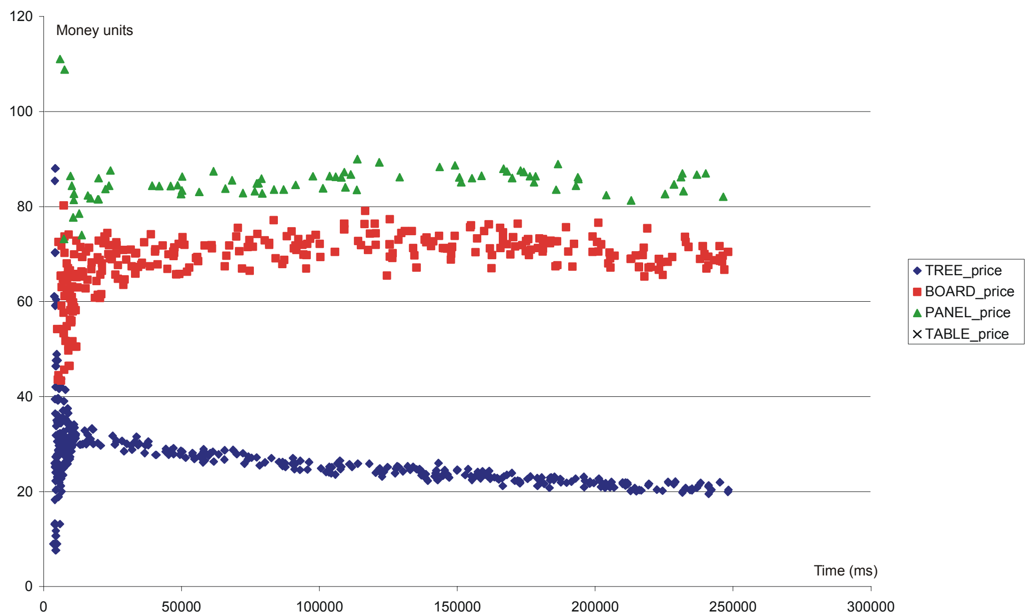

Figure 4. Experiment 1 — Self-Organization through Price Negotiation

A showcase test run based on randomly initialized price concepts of the agents is illustrated in figure 4, in which each individual point represents a successfully concluded transaction and marks the sales price of the goods. It shows that after some transactions have been conducted and the agents begin to adapt their strategies, a price band results for the products of the individual net product stages and a stable coordination (spontaneous order) is produced.

Change of Behaviour Using a Regulatory Framework

A prerequisite for the development of spontaneous order is that all parties involved accept the regulation framework implemented for the market coordination mechanism. In a second scenario we drop the implicit assumption of "honest traders" (Eymann et al. 2002); Agents now appear which behave fraudulently and, as purchasers, do not pay for goods received or, as sellers, do not deliver paid goods. In an initial stage, the experiments show that such behavior leads to a short-term profit optimization of the fraudulent agents, though usually also results in the collapse of the entire system. In a second step, it can be demonstrated that fraudulent agents can in actual fact be excluded through a decentral consideration of the risk of fraud in the form of reputation information, the collapse is prevented and a "better" (in the sense of "more robust") spontaneous order can be developed.

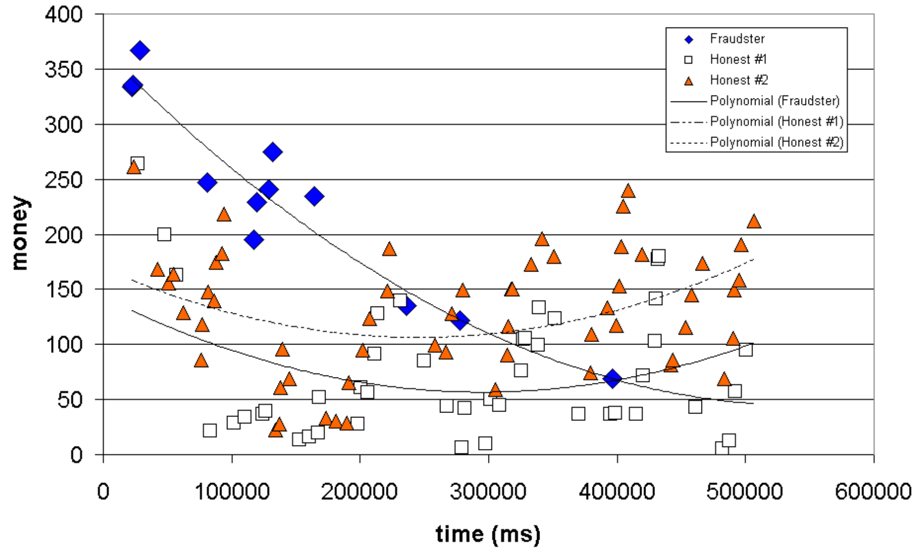

Figure 5. Experiment 2 — Self-Organization through Decentral Adaptation of the Behavior Rules

Figure 5 shows that the wealth (the economic success) of a fraudulent agent (rhombus) is relatively high at the start of the simulation, but quickly declines on recognition of its violation of the rules, which the other agents recognize. This experiment shows the significance of strategic behavior for the maximization of personal interest both in the application of institutions as well as in the leading of negotiations. It is therefore important for the agents to record the context relevant for their strategy and to include this observation in their behavior.

Context Recognition and Self-Organization

In a third simulation scenario (Sackmann 2003), the agents are fitted with an additional measuring system for mapping their environment which enables them, after a few transactions, to evaluate the negotiation leeway specific to the marketplace. This context information is used for the adaptation of personal negotiation behavior and determines the establishing of initial offers and the course of the opening of the negotiation. In addition to the transactions realized (dark rhombi), figure 6 also shows the initial offers of both sides of the market (sellers as circles, buyers as light rhombi).

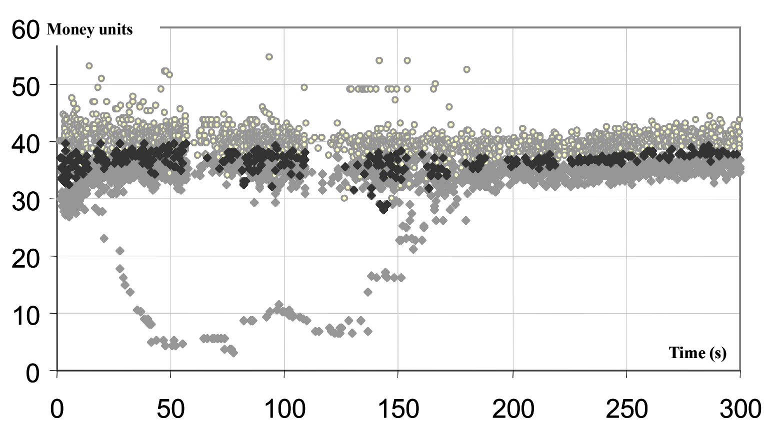

Figure 6. Experiment 3 — Self-Organization through Context Recognition

One of the purchasing agents enters an ongoing market. This agent has in fact a good subjective estimation of the latest market price, yet a completely wrong idea of the usual size of initial offers (light rhombi which lie below the "normal range"). Without the ability to recognize the negotiation behavior characteristic of the marketplace, such an agent has no chance of operating to the best advantage. Through context recognition via the implemented measuring system, it is however possible to adapt personal behavior to the typical marketplace behavior. Thus, the initial offers move towards the negotiation behavior of other players in the marketplace can, after a few transactions, no longer be distinguished.

Self-Organization in Patient Logistics

So far, results and experiences with the self-organization of multi-agent systems have given reason for the assumption that decentralized information systems can be self-organizationally realized using Hayek's Catallaxy concept. Whether these hopes are justified must however be demonstrated outside the experimental system in a real application scenario and also by the implementation of a real technology infrastructure.

The task of information systems used in hospital patient logistics should be to schedule inpatients and outpatients to equipment and personnel, according to medical priority so that as few hold-ups as possible occur, and the patients' examinations take place on time. Despite the existence of up-to-date centralized planning and information systems, the hospital staff usually schedules using telephones and beepers, but not the available computers. The necessity for immediate reaction to sudden alterations, e.g. in the case of emergencies or delays, and the prompt relaying of amended information to all parties concerned, is currently not satisfyingly realized in these information systems.

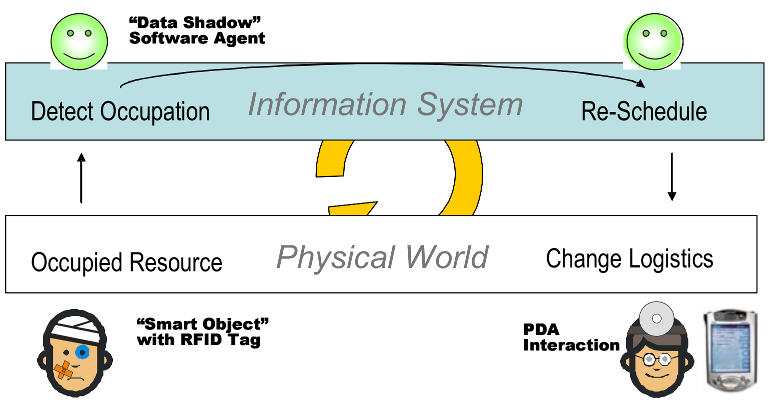

Figure 7. Feedback loop in a UC-Based Patient Logistics Application

Planning in patient logistics and in the medical treatment paths reach their limits on account of such dynamic general conditions – the event of an emergency can not be planned in advance. Each concrete reservation plan or transportation must be regarded as temporary and alterable from the time made until its final conclusion. Through conscious overbooking, the full utilization of examination equipment can of course be guaranteed but, on the other hand, it involves high lengths of stay for inpatients, long waiting periods and poor transport scheduling.

The EMIKA project aims to provide a software application which uses various technologies of ubiquitous computing in order to overcome the challenges of patient logistics. The technologies thereby enable the individual system components to perceive their physical surroundings, to recognize location and condition and to model the reality. Intelligent software agents undertake this task as "shadow objects" of the end devices. They autonomously decide whether the actual schedule can be adhered to or whether rescheduling of equipment and persons is necessary in order to achieve a better utilization of resources. In the case of negotiations on new appointments, they try to optimize their own utility: patient agents minimize the throughput time, agents of examination equipment maximize the capacity utilization. If a doctor receives a new appointment, he is informed via his PDA, patients get a message on the screen of their mobile phone. This results in a continuous dynamic feedback between reality and information system, without a central entity controlling the system on the fictitious basis of complete information.

This no doubt raises the question as to who defines the framework. Will the treatment costs be the decisive factor, must patients obey a voucher or credit point system, and does scheduling using autonomous computers affect the quality of the medical care?

Can Hayek be Automated?

A key concern of Hayek's thought is the "fatal conceit" (Hayek et al. 1989) of assuming, that it is principally possible to achieve a complete and concise picture about a large system. This might be true even in times of increasing miniaturization of storage and processors and the computerization of everyday objects. However, if the system in question is small enough and all tasks can be described and programmed, central coordination might still be the better applicable way (Malone und Crowston 1994). As we move on to technology, which allows us to map unstructured semantic knowledge in large and very dynamic systems, we have to look for decentralized self-organization, not at least for reasons of exponentially increasing "costs of ownership" (IBM Corp. 2001; Truex, Baskerville und Klein 1999).

Hayek's claim was that such a coordination mechanism already exists in the price mechanism, and that we only have to realize that and transfer it in the realm of information system. This article has demonstrated in three experiments that communication through price signals guides the formation of an institutional regulation framework and the processing of context information to a self-organized order. It is, however, similarly possible to disrupt the self-coordination through targeted violation of the "regulatory framework". The automated pursuit of the individual goals does not alone produce an acceptable behavior of the entire system, e.g. in terms of robustness, controllability and the adherence of security criteria for the individual participant.

Figure 8 shows how continuously evolving information systems will probably come into existence. Realizing and implementing a small multiagent system, like the ones shown in this article, is only the first step. The goal of these small systems is to generate automated, coherent action of the end-user devices (or their shadow objects, as in the EMIKA patient logistics project). The self-coordination aspect of the Catallaxy leads to a spontaneous order. To maintain this order, both the devices/agents and the software designers of the original system have to adapt to changing environments and participants. By way of a cultural evolution, rules of acceptable behavior get refined and give way to the next version of system inhabitants, who will be released in the information system and shape it to their needs. The final open question is, whether the spontaneous order provides "acceptable behavior" of the system – in principle, spontaneous order has no conscience. For the patient logistics system, if the rules of the game are not properly specified, the spontaneous order might prefer those patients who are able to pay cash, which is not an acceptable behavior.

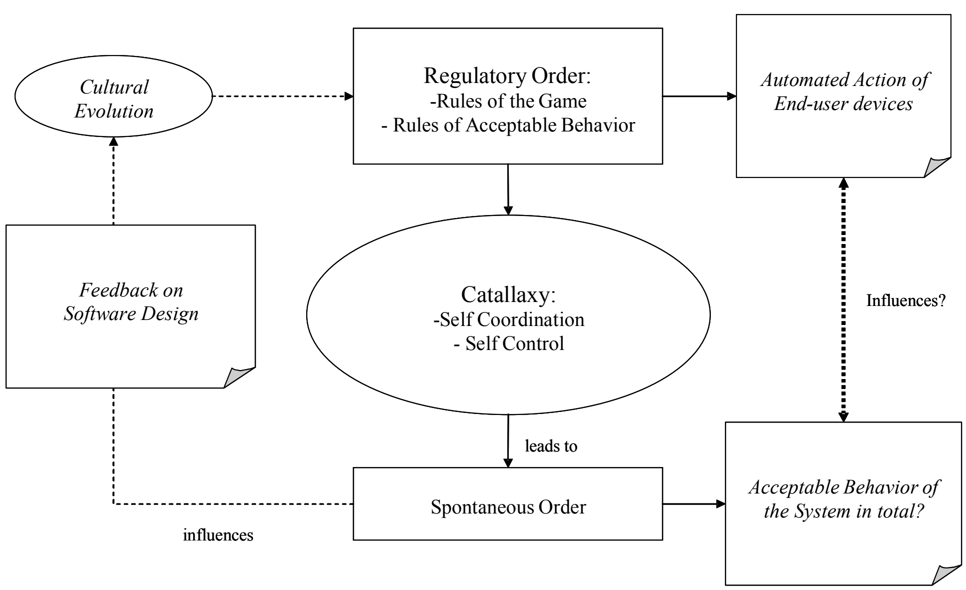

Figure 8. Design of Information Systems Using the Catallaxy

For information systems in general, the question is raised as to whether these perceptions can be generalized and used for the design of decentralized information systems (or information systems in a decentralized environment) and lead to more efficient paradigms there for the implementation of computers. The evaluation of technology in the sensitive application domain of the hospital will show acceptance barriers which lie beyond the technology sphere. The constant transfer of location and status data into the information system leaves fears about privacy and security, whilst the coordination via price signals raises the question as to what effects a market failure would have on vital examinations and emergency patients.

The described experiments do not provide any recipes to transfer results to other systems or other application domains. The question remains open as to which is the most effective framework to achieve spontaneous order. The necessary regulation framework required for this, which needs to be automated for the operative implementation in information systems, can *ex ante* only be specified as trial and error. However, we hope that more cost-effective design processes and general conditions befitting the new technology can be found. Self-organization will, in our opinion, then become the main principle for decentralized coordination of multi-component information systems.

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